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THE DISTRIBUTION OF LAND AND WATER ON THE EARTH.

By HARRY FIELDING REID.

(Read April 22, 1920.)

The shapes of the various continents and seas, their relative areas, and their dispositions with regard to each other, have always been attractive problems for geographers; and a number of characteristics have been formulated, which have been repeated in various text books of geography and geology, and have thus become familiar to us all. They are:

1. The earth can be divided into two hemispheres in such a way that nearly all the land is concentrated in one hemisphere, and the other is nearly all covered with water.

2. The land is everywhere opposite the water.

3. The land is concentrated around the arctic regions, and the water around the antarctic regions. The land sends three projections towards the south, and the oceans three projections towards the north.

5. The continents are roughly triangular in shape, pointing southward. The oceans are roughly triangular in shape, pointing northwards.

6. The continents are divided into a northern and a southern group by mediterranean seas; and the southern group is offset towards the east.

I imagine we have all pondered over these curious characteristics; and I must confess that the antipodal relation of land and water has, until recently, been to me an absorbing though baffling mystery, with no threads leading to its solution. But the matter turns out to be rather simple, after all. It can be shown that nearly all the characteristics enumerated above are comprised in the following: *The land area of the earth is a loosely connected, and deeply dissected area, about five-sixths of which is concentrated in*

one hemisphere, whose pole lies about half way between the equator and the north geographic pole. And the position of this land area on the earth has no relation whatever to the earth's equator and axis of rotation.

A glance at Fig. 1 will show that this is a true statement; we shall discuss later this concentration of the land.

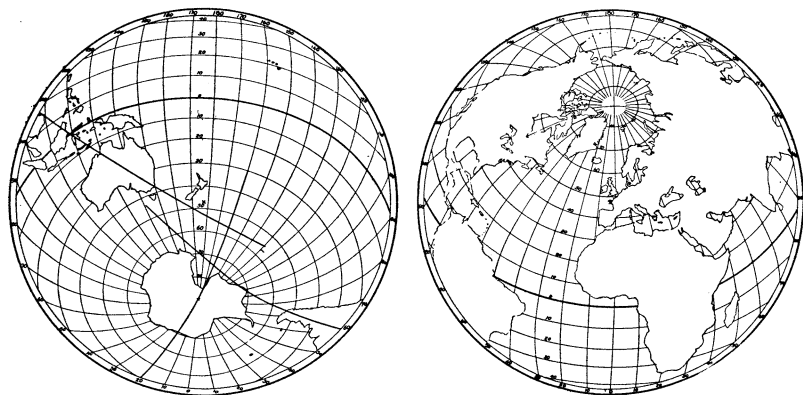


FIG. 1. Land and water hemispheres. Lambert's equivalent area projection.

1. The first characteristic is explicitly contained in the general proposition above.

2. A glance at Fig. 2, taken from Stieler's Handatlas, impresses one strongly with the antipodal relation of land and water; but Fig. 3 gives a truer impression. The former shows the eastern hemisphere with the western hemisphere projected through upon it, the latter shows the land hemisphere with the water hemisphere projected upon it.¹

If all the land were in one hemisphere, then the antipodal relation of the land to the water would be perfect. But this is not so; there is some land in the water hemisphere. Does it project upon water in the land hemisphere?

¹ The center of the land hemisphere has been pretty carefully worked out by H. Beythien ("Eine neue Bestimmung des Pols der Landhalbkugel," Dissertation. Kiel und Leipzig, 1898) following a method suggested by Professor Krümmel. He places the center at latitude $47\frac{1}{4}^{\circ}$ N. and longitude $2\frac{1}{2}^{\circ}$ W., close to the mouth of the Loire. Using a slightly different method I have corroborated his results.



FIG. 2. Antipodal relations. Globular projection. From Stieler's Handatlas.

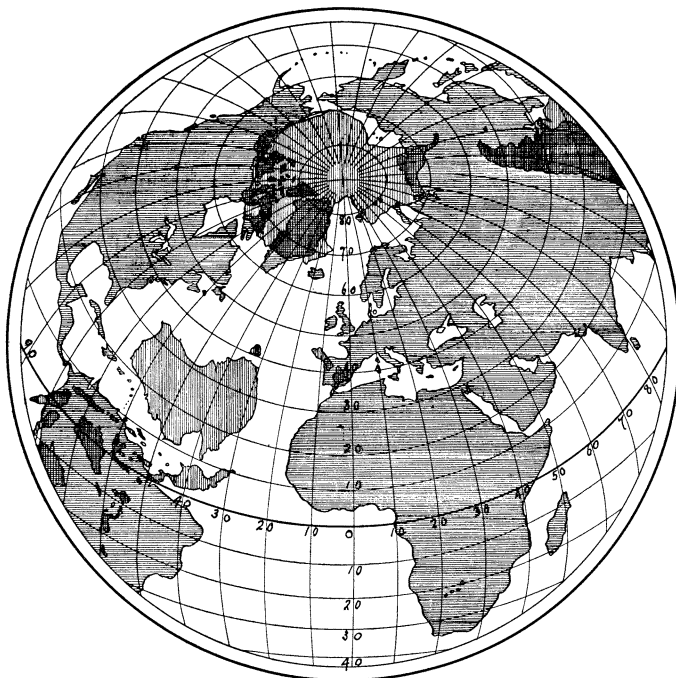


FIG. 3. Antipodal relation of land and water hemispheres. Lambert's equivalent area projection.

There are three main land masses in the water hemisphere: Australia, with some of the large islands north of it; the Antarctic continent, and the southern end of South America; to these may be added the much smaller area of New Zealand. Fig. 3 shows that Australia projects against the North Atlantic Ocean; and some of the adjacent islands against the northern part of South America; the southern part of South America projects almost entirely against China; the Antarctic continent projects partly against the Arctic Ocean and partly against the lands surrounding it. New Zealand projects partly against Spain and partly against the adjacent sea. The total area of the lands in the water hemisphere is about one eleventh of the area of the hemisphere. A little less than one half this land projects against water and a little more than one half against land, and this is almost exactly the proportion we should expect if the land in the water hemisphere were distributed without any definite relation to the water in the land hemisphere. For in the latter the ratio of the land to the water is 1 : 1.1; *i.e.*, practically one half the hemisphere is water and one half is land. So far then as the antipodal relation of land and water is not explained by the existence of a land and a water hemisphere, it is purely accidental; and there is no necessity to look for a special explanation for it.

3. The fact that the center of the land hemisphere is pretty far north, being a little more than half way from the equator to the north pole, places the arctic regions well within this hemisphere and therefore naturally surrounds them with land. And similarly the antarctic regions being well within the water hemisphere is naturally surrounded by water.

4. If you draw on a sheet of paper the outline of any fairly compact area and then divide it up by deep indentations, you will have left a figure with projections pointing roughly away from the center. Now this is exactly the characteristic of the land area of the world. The projections of South America, Africa, and Australia are said to point towards the south. Our predilection for referring everything to the earth's axis of rotation has blinded us to the fact that these projections of the land area point equally well towards the antipodes of the center of the land hemisphere, *i.e.*, in

a general way, away from the land mass; a relation which is a natural consequence of the concentration of the land in one general mass. The strong lines in Fig 1 are great circles extending the directions of the three projections.

But why should there be just three such masses? I can give no definite answer to this question and I am not sure that there is a real answer to it.² In a dissected land area, such as we find on the earth, there must be some number of projections, and the number will depend upon how broadly or how minutely the land is dissected; and their importance on how much we are impressed by the shape of the projections. Japan and Mexico, for instance, are quite as far from the center of the land hemisphere as the south end of Africa (see map, Fig. 1); but in their neighborhood the outline of the land maintains its distance from the center and we are not impressed by this distance.

5. The triangular shape of the continents and oceans is far too rough an approximation to have any real importance. A glance at special maps in a good atlas will show how far from triangular they are. South America is distinctly triangular; North America is not; Eurasia is not. Africa has more the shape of a carpenter's square. The northern part of the Pacific Ocean is bounded nearly by a great circle, that is the boundary is as nearly a straight line as can be drawn on the globe. Here again the maps made on a Mercator projection have suggested the idea of an ocean narrowing towards the north. The boundary of the Indian Ocean on the north is nearly a small circle, not in the least a corner of a triangle. Nor do the North and South Atlantic Oceans at all follow a triangular shape. I think the suggestion of a triangular shape for the oceans and continents is too vague to have any meaning or any value and may be abandoned.

6. Is this of real significance? South America is certainly well separated from North America; and Australia from Asia; but Australia is really a very big island and is only a continent by courtesy. The separation of Africa from Europe is quite insignificant. It has been suggested that the mediterraneans are the indications of a zone of weakness lying along what was once the earth's

² See, however, a few pages further on.

equator, with the pole in Behring's sea; that the southern hemisphere contracted more than the northern and thus tended to increase its rate of rotation, producing stresses which caused fractures along the then equator. Aside from dynamical objections to such a process, we note that Africa is not offset along the Mediterranean; only its southern part is offset. So that the explanation offered does not apply to the conditions in attempts to explain. Here again our predilection for the geographical north and south line brings its influence to bear, and we think that the continents should naturally lie north and south, and that any deviation from that direction needs an explanation. But this is not so. In this particular case, however, the southern ends of the three land projections lie all three somewhat to the east of the northern parts, and this uniformity is striking. But notice this: if these southern ends do not lie directly south of the northern parts, two of them must be apparently displaced in one direction; the third might be displaced in the same or in the opposite direction; that it should happen to be in the same direction is not remarkable.

I think, therefore, we may agree that the main characteristics of the distribution of land and water on the globe is contained in the statement given in italics near the beginning of this paper.

Why should we have a land hemisphere and a water hemisphere? The answer given by Herschel, about 60 years ago, is the true answer, though to be sure, it only points the direction in which further knowledge should be sought. Herschel's explanation was that the center of mass of the earth and its center of figure do not coincide.

Let us examine this a little more closely. If the material of the earth were distributed with perfect symmetry about the center of mass the ocean would cover the whole earth to a uniform depth. But if one hemisphere were slightly denser than the other the water would be drawn to that side and make a deeper ocean there.

How can we explain this lack of symmetry? We could easily imagine that the earth, in whatever manner it may have developed, might be lacking in symmetry sufficient to bring about the small separation, about a mile and a half, between its center of mass and

its center of figure. This would infer the permanence of the Pacific Ocean, still a moot question among geologists; and we must also remember that Hayford and Bowie have shown that under the continent of North America, and, in a less convincing degree, under the adjoining oceans, isostatic adjustment is complete at a very small depth; and it is only in this surface skin therefore that the density of the earth is different in the two hemispheres. In many parts of the known continental areas the rock has undergone changes of density, with corresponding changes of level; whether such changes have extended over very large areas so as materially to change the distribution of land and water on the globe is the still unanswered problem of the permanence of the ocean basins. Imagine an earth, spherically symmetrical in density; now imagine that the crust in one hemisphere to a depth of 100 miles contracts so as to shorten the central radius by 3 miles and that this shortening gradually diminishes to zero along the edge of the hemisphere. A simple calculation shows that the crust to a depth of 100 miles would be increased in density about 3 per cent.; that the center of mass of the earth would be displaced only about 70 feet, so that the level surfaces would remain practically unchanged; and therefore the ocean in the center of the contracted hemisphere would be about 3 miles deeper than in the antipodal region. This apparently is what has occurred, but why the contraction should be especially marked and so general over one hemisphere is still unknown.

The only attempt to explain the hemispherical distribution of density is that of Osmond Fisher.³ He suggests that the material that formed the moon, according to George H. Darwin's theory, was collected from the superficial part of the region which is now the Pacific Ocean, and was therefore of comparatively small density. The scar was healed, to a large extent, by denser material from below, and the two Americas were, at the time of separation of the moon, cracked off from Europe and Africa, and floated to the west, leaving the Atlantic basin underlaid by the denser material below. This hypothesis is purely speculative. It runs counter to other geo-

³ *Nature*, 1882, XXV., 243; also "Physics of the Earth's Crust," 2d ed., 1889, XXV. W. H. Pickering offered the same explanation. "The Place of Origin of the Moon," *Jour. Geol.*, 1907, XV., 23-38.

logical speculations, such as a land connection between Africa and Brazil in middle geologic times, and a similar connection across the North Atlantic in Tertiary times.

Some attempts have been made to explain the existence of oceans and continents. Lowthian Green advanced the tetrahedral hypothesis in 1875.⁴ The corners and edges of the tetrahedron are supposed to be land areas, and the faces water areas. The advocates of this hypothesis differ materially in locating the corners and the edges; and the dynamical arguments in favor of the tetrahedral form are entirely unsound.

In 1878 George Darwin⁵ suggested that under the tidal action of the moon north-south wrinkles might develop, which would later, under the same forces, have their equatorial portions pulled towards the west. The general form of the continents conform but slightly to this plan, and the geologic structure is largely at variance with it.

The idea of an earth cooling and contracting goes back to the time of Leibnitz. Dana⁶ suggested that the portions of the earth's crust which solidified first would blanket the rock under them and keep it warm; these regions would become continents; whereas, violent convection in the still liquid regions would bring more heat to the surface there and dissipate it, thus cooling these parts, and causing them to contract more and become the ocean beds.

Pratt's studies of the deflection of the vertical in India led him to the conception now denoted by the name of isostasy; he considered that the difference of density under the continents and oceans was due to unequal contraction, but he did not assign any cause of this inequality.⁷

Faye,⁸ accepting Pratt's conclusions, ascribed the greater density under the ocean to the lower temperature there. Taking the temperature of the sea bottom at a depth of 4000 m. at 1° C., the mean surface temperature of the land (at sea level) at 16°, and the tem-

⁴ "Vestiges of a Molten Globe," Honolulu, 1875.

⁵ Problems Connected with the Tides of a Viscous Spheroid," *Proc. R. S.*, 1878, XXVIII., 194-199, and *Phil. Trans. R. S.*, 1879, CLVII., 539-593.

⁶ "On the Volcanoes of the Moon," *Amer. Jour. Sci.*, 1846, II., 335-355.

⁷ "Figure of the Earth," 4th ed., 1871, pp. 201, 202.

⁸ "Sur les variations séculaires de la figure mathématique de la Terre," *C. R.*, 1880, XC., 1189-91.

perature gradient at 1° C. per 33 m. the temperature under the land at the same level as the sea bottom would be $16^{\circ} + \frac{4000}{33} = 149^{\circ}$.

Trabert⁹ carried Faye's idea a step farther. He assumes a land surface temperature of 10° C., a temperature gradient of 3° per 100 meters, and a mean ocean depth of 4300 meters, with a bottom temperature of 0° ; and thus gets a difference of 140° . He then calculates what would be the difference of average temperature of two cones, extending to the earth's center, one under the land and one under the sea, sufficient to account for a difference in length of 5000 meters, which he gets roughly by adding the mean height of the land to the mean depth of the ocean. He finds the relation $aRT = 5000$ m., where $a = .00001$ is the coefficient of expansion of the rock, R the radius of the earth, and T the average difference of temperature of the two cones. This gives $T = 78^{\circ}$, which, in view of the difference of temperature of the sea bottom and the same level under the land, he considers a very reasonable figure; and therefore thinks the ocean basins are entirely due to low temperature of the underlying rock.

But it is quite impossible for the two cones to differ by anything like 78° in mean temperature. Both Faye and Trabert were misled by comparing the temperatures at the sea bottom level. This difference has no bearing whatever on the difference in the mean temperatures of the two cones. To illustrate: Suppose we have two cones of exactly the same size, and with a similar distribution of temperature; for simplicity, suppose the temperature is diminishing continuously from the apex to the base. Now let one of these cones expand uniformly, each of its elements keeping its temperature. Its mean temperature will not have changed at all; it will still be the same as that of the other cone; but at the same distance from the apex it will have a higher temperature than the other cone. It is easy to imagine a distribution of temperature which would yield a great difference between the two cones at the level of the base of the unchanged one; though the mean temperatures of the two cones

⁹ "Eine mögliche Ursache der Vertiefung der Meere," *Sitz. Kais. Ak. Wiss. Wien, Math. Nat. Kl.*, 1911, Bd. 120, Abt. 2 A, 175-180.

remain the same. All that is necessary is that the temperatures should change rapidly near the bases of the cones.

Let us calculate the difference of mean temperature of the land and sea cones under some simple distributions of temperature. Suppose the apices of the cones to have the same temperature and the bases to differ by 16°C. ; and suppose the temperature gradient to be uniform in each cone from the apex to the base. An easy calculation shows that the difference of the mean temperature of the cones would be three quarters of 16° , or 12° . And with the coefficient of expansion adopted by Trabert, this would account for a difference of level of the bases of 770 meters, or about one seventh of the actual amount. A constant temperature gradient in the earth is of course impossible. With a gradient of 1° per 100 meters, which is certainly smaller than that observed at the surface, we should have a central temperature of over $127,000^{\circ}$.

As a second example let us suppose that the earth has cooled in accordance with Lord Kelvin's theory. We shall take the original temperature at 1170° , the present land surface temperature at 16° , the sea bottom at 0° . For the sake of making the difference as great as possible, we shall assume an age for the earth of 500 million years. We find that below a depth of one tenth of the radius the two cones have practically the same temperature and that the mean difference in the two shells above this depth is somewhat less than 4° , accounting for a difference of level of the bases of the two cones of about 25 meters.

If we ascribe the earth's heat to radioactive substances, we are confronted with our ignorance of the relative quantities under the land and under the sea. They seem to be somewhat more abundant in the more siliceous rocks of continental areas, though the red clay of the deep sea seems to have a high content; on the other hand the less siliceous rocks of the oceanic areas have a lower conductivity for heat. We may then as a rough approximation assume that the temperature curve has the same form under the two regions, differing, however, by 16° in temperature at the same depth below the surface. This would only hold for moderate depths, say, for a few hundred miles. Farther than this there would be a diminution

of the difference due to the flow of heat from the regions below the continents to those below the oceans, so that the mean difference of our two cones would be less than 16° . A mean difference of 16° would account for about 1000 meters difference of level at the earth's surface.

It seems difficult to imagine any probable distribution of temperature in the earth that would cause a difference as much as 16° in the mean temperature difference of oceanic and continental cones. And this is only about one-fifth as much as Trabert asks to account for the difference of elevation of 5000 meters; and when we consider that there are considerable tracts of sea bottom and of plateau land that differ in level by twice that amount it seems to exclude a mere difference of temperature as a sufficient cause of the different levels of the earth's surface. As further confirmation of this conclusion we notice that the antarctic continent and Greenland are buried under ice which keeps their surface temperature quite as low as the sea bottom, and still they are both land areas.

Joseph LeConte¹⁰ ascribed the ocean basins to greater cooling and contraction on account of greater conductivity for heat of the underlying material. What little information we have on this subject is opposed to the idea. For basaltic rocks, which characterize the oceanic areas, have a smaller conductivity and diffusibility than the granitic rocks, which are mainly continental, or the sedimentaries.

Sollas¹¹ has suggested the following, on the hypothesis of a cooling earth: When the earth was still very hot, all the water would be in the atmosphere as vapor, and would exert practically a uniform pressure on all parts of the earth. When the temperature fell sufficiently for this water to exist in a liquid form it would occupy the slight depressions which must have existed, increasing the pressure there and reducing the pressure over the high regions. As the crust of the earth was then very near its melting point and the pressure due to the water was important, there may have been considerable compression under the oceans and expansion else-

¹⁰ "A Theory of the Formation of the Great Features of the Earth's Surface," *Amer. Jour. Sci.*, 1872, IV., 345-355, 460-472.

¹¹ *B. A. A. S.*, 1900, pp. 714-716.

where, combined with a squeezing out of some material from under the seas. It is not clear how this expansion could have been maintained as the crust cooled.

Chamberlin thinks that the earth is divided into six segments, three in the northern hemisphere and three in the southern; that the edges of these segments would be squeezed up leaving the depressed faces as the incipient ocean basins; that a preponderance of heavier planetesimal matter was deposited under areas of high barometer; that there were three such areas in the southern hemisphere, partly on account of the three segments, but also on account of "the peculiar spacial requirements of a hemisphere."¹² (It may be remarked that this requirement of a hemisphere is not recognized by mathematicians, geophysicists, or meteorologists, and there are only two areas of high pressure in the northern hemisphere, which also change with the seasons.) Chamberlin also thinks that the heavier materials in the crust were carried by erosion to the oceans leaving lighter materials on the continents; and the accumulation of heavier material perpetuated and accentuated the ocean basins. The hypotheses on which this explanation is based are far too numerous to make it at all acceptable.

In 1873 Dana looked upon the greater density under the ocean as due to the character of the mineral ingredients there, but could not account for their distribution.¹³ Iddings has pointed out that the rocks collected from the Pacific islands, have, on account of their composition, a higher density than the rocks of the continents, and, so far as our knowledge goes, fit in with the general principle of isostasy.¹⁴

We may say, in closing, that the existence of a water hemisphere and a land hemisphere is due to the non-coincidence of the center of mass and the center of figure of the earth; that this is due to a difference of density in the two hemispheres, probably confined to a hundred miles or so of the surface; and that this, in turn, is due, not to unequal contraction or anything of that kind, but to a difference in the composition of the rock in the two areas.

¹² "The Origin of the Earth," Chap. VIII., Chicago, 1916.

¹³ *Amer. Jour. Sci.*, 1873, VI., 168-169.

¹⁴ "The Problem of Volcanism," pp. 123-125.